REPOP 'OCUMENTATION PAGE

AFRL-SR-BL-TR-98-

0L031

Public reporting burden for this collection of information is estimated to average 1 hour per response, including ... hering ... and maintaining the data needed, and completing and reviewing the collection of information. Send comme... llectio... o information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate fc... ay, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (07...

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPO...
	May 27, 1998	Final Report (Aug 1995-Feb 1998)

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Doppler Radar and Analysis for Climate Model Verification and Numerical Weather Prediction	Grant # F49620-95-1-0320
6. AUTHOR(S) Qin Xu and Richard J. Doviak	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) University of Oklahoma 100 East Boyd, Room 1110 Norman, OK 73019	8. PERFORMING ORGANIZATION REPORT NUMBER N/A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Air Force, Office of Scientific Research	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Unlimited	

13. ABSTRACT *(Maximum 200 words)*

Towards the originally proposed research goal, a least square (LS) method was developed for retrieving low-altitude winds from Doppler radar observations. The method was tested with Denver Airport microburst data and the results compared with the previously developed simple adjoint (SA) method. It was found that the LS method was slightly superior to the SA method for the microburst data obtained with fast radar scans, but became inferior to the SA method when the radar scans were twice as long (Qiu and Xu, 1996, *Mon. Wea. Rev.*, 1132-1144). The LS method was further upgraded to including background wind fields and used to improve the initial condition for the ARPS model's short-term prediction. A variational method was also developed to assimilating surface mesonet data and compute the surface fluxes of sensible and latent heat. The new method overcame the drawbacks of conventional Bowen Ratio Energy Balance method and Profile method (PROF). This method made a better and more complete use of the data and the constraints provided by the surface energy balance equation and the similarity profile equations (Xu and Qiu, 1997, *J. Appl. Meteor.*, 3-11). In addition, studies supported by this grant generalized the classic adjoint method for meteorological data assimilation (Xu, 1996, *J. Atmos. Sci.*, 1123-1155, and Xu, 1997, *J. Atmos. Sci.*, 2713-2728).

14. SUBJECT TERMS	15. NUMBER OF PAGES
Doppler Radar Analysis, Model Verification	3
	16. PRICE CODE

DTIC QUALITY INSPECTED

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL

Final Report

(May 10, 1998)

Submitted to

the U. S. Air Force Office of Scientific Research

by

Former Principal investigator: Qin Xu
Cooperative Institute for Mesoscale Meteorological Studies (CIMMS)
University of Oklahoma, Norman, OK 73019

Principal investigator: Richard J. Doviak
National Severe Storms Laboratory
1313 Halley Circle, Norman, Oklahoma 73069

for

Grant No. F49620-95-1-0320

Doppler Radar Wind Analysis for Climate Model Verification and Numerical Weather Prediction

1. Goal and Objectives:

The goals of the originally proposed research was to explore the potential use of the new data resource from the network of National Weather Service's WSR-88D Doppler weather radars and to develop advanced methods of mesoscale data assimilation that use Doppler radar data in combination with other available data. Towards this goal, three research objectives were proposed: (a) to upgrade the VAD technique, (b) to retrieve low-altitude winds from single-Doppler and surface mesonet measurements, and (b) to improve the background wind analysis in three dimensions.

2. Summary of Research Effort

Towards the research objective (a), effort was made on improving the previously developed Lagrangian advective scheme to estimate large scale vorticity using VAD products and reflectivity. A Lagrangian advective scheme was designed to estimate large scale vorticity using VAD products and reflectivity, and the code development work was performed by graduate students at the School of Meteorology supported by this grant. Effort was also made on combining the VAD technique with the simple adjoint method and least square method. The simple adjoint method and least square method was able to retrieve winds on a high resolution grid, but the area-averaged divergence of the retrieved wind field was found to be dependent on the grid resolution (see Fig. 1 and attached discussion in Progress Report of Y97). On the other hand, the VAD-estimated divergence was quite accurate as shown by the recent study of Lu, Doviak and Crisp (1996, *J. Atmos. & Oceanic Technology*, 1129-1138). This suggested that the divergence profiles, estimated from application of Gauss's theorem at different radii, might be used as additional constraints to improve the simple adjoint and least square retrievals. This idea needs to be further explored.

Towards the research objective (b), effort was made on developing new variational methods for single-Doppler wind retrieval and surface mesonet data assimilation. The related accomplishments are reported in sections 3a and 3b. Effort was also made on developing new additional techniques to improve the simple adjoint (SA) method and least square (LS) method for retrieving low-altitude winds from single-Doppler scans. One promising new technique was to use truncated empirical orthogonal functions to filter noise caused by data errors and/or data holes. To incorporate this idea into the SA and LS methods, truncated empirical orthogonal functions (EOFs) were used to filter noise caused by data errors and/or data holes. EOFs were obtained from the eigenvactors of the time-spatial correlation matrix of the wind fields retrieved (by the SA or LS method) over the previous N-1 time levels. When the correlation matrix was extended to include the observed radial wind fields (over the N time levels), the vector wind field at the N-th time level was constructed by truncated EOFs even without using the reflectivity equation and radial wind equation. The preliminary results showed that the EOF constructed wind field could be more accurate than the SA (or LS) retrieval (see the attached Figs. 4a-b and Table 1 in Progress Report of Y96).

Towards the research objective (c), the LS method was upgraded by including background wind fields from O-LAPS (the Oklahoma Local Analysis and Prediction System). The retrieved winds were used together with surface mesonet data to improve the O-LAPS analysis and short-term weather prediction (see section 3c).

3. Accomplishments

a. Single Doppler wind retrieval

A least square (LS) method was developed for retrieving low-altitude winds from single-Doppler scans. The method was tested with Denver Airport microburst data and the results compared with the previously developed simple adjoint (SA) method. It was found that the LS method was slightly superior to the SA method for the microburst data obtained with fast radar scans (every 60 s), but became inferior to the SA method when the radar scans were twice as long (every 120 s). Four previously developed detailed techniques for the SA method were used to improve the LS retrievals, and these include (i) using multiple time-level data, (ii) imposing the weak divergence and weak vorticity constraints, (iii) retrieving the eddy coefficient and time-mean forcing term, and (iv) using the observed time-mean radial wind as a weak constraint. Because the control equation was used as a weak constraint in a finite-difference form, the LS method depended more on the smoothness constraints, but was less sensitive to equation error and computationally much more efficient than the SA method (Qiu and Xu, 1996, *Mon. Wea. Rev.*, 1132-1144).

b. Surface mesonet data assimilation

A variational method was developed to assimilate surface mesonet data and to compute the surface fluxes of sensible and latent heat. The new method overcomes the drawbacks of conventional Bowen Ratio Energy Balance method and Profile method (PROF). This new method makes a better and more complete use of the data and the constraints provided by the surface energy balance equation and the similarity profile equations (Xu and Qiu, 1997, *J. Appl. Meteor.*, 3-11).

c. Using single-Doppler retrievals to improve short-term prediction

The LS method was upgraded by including background wind fields from O-LAPS (the Oklahoma Local Analysis and Prediction System). The upgraded method was applied to single-Doppler data collected by the NEXRAD radar at Twin Lakes on 7 May during the 1995 Oklahoma Vortex Field Experiment. The retrieved winds were used together with surface mesonet data to improve the initial condition for the ARPS model's short-term prediction. The preliminary results were encouraging (see Figs. 2-4 and attached discussion in Progress Report of Y97).

d. Generalized adjoint for mesoscale data assimilation

The classic adjoint method has been successful in meteorological data assimilation with variety of dynamic models, but is not applicable to physical processes that contain parameterized discontinuities. The problem becomes acute in recent years, because much attention in adjoint data assimilation has turned to physical processes, especially for storm-scale. To solve the problem, the classic adjoint theory was generalized (Xu, 1996, *J. Atmos. Sci.*, 1123-1155) and the generalized adjoint method was developed to deal with various complex situations in atmospheric numerical models (Xu, 1997, *J. Atmos. Sci.*, 2713-2728).

4. Personnel Supported:

PIs: Qin Xu, Richard J. Doviak, Ming Xue;
Graduate students: Swarmdeep Gill, Penfei Zhang, Binbin Zhou;
Research scientists: Wei Gu, Hangdao Gu.

5. Publications (6 Journal publications acknowledging this grant)

1. Qiu, C., and Q. Xu, 1996: Least-square retrieval of microburst winds from single-Doppler radar data. ***Mon. Wea. Rev.***, **124**, 1132-1144.
2. Xu, Q., and C. Qiu, 1997: A Variational method for computing surface heat fluxes from ARM Surface Energy and Radiation Balance Systems. ***J. Appl. Meteor.***, **36**, 3-11.
3. Xu, Q., 1996: Generalized adjoint for physical processes with parameterized discontinuities – Part I: Basic issues and heuristic examples. ***J. Atmos. Sci.***, **53**, 1123-1142.
4. Xu, Q., 1996: Generalized adjoint for physical processes with parameterized discontinuities – Part II: Vector Formulations and Matching Conditions. ***J. Atmos. Sci.***, **53**, 1143-1155.
5. Xu, Q., 1997: Generalized adjoint for physical processes with parameterized discontinuities – Part III: Multiple threshold conditions. ***J. Atmos. Sci.***, **54**, 2713-2721.
6. Xu, Q., 1997: Generalized adjoint for physical processes with parameterized discontinuities – Part IV: Problems in time discretization. ***J. Atmos. Sci.***, **54**, 2722-2728.

Progress Report

(September 1, 1997)

Submitted to

the U. S. Air Force Office of Scientific Research

by

Principal investigator: Qin Xu
Cooperative Institute for Mesoscale Meteorological Studies (CIMMS)
University of Oklahoma, Norman, OK 73019

Principal investigator: Richard J. Doviak
National Severe Storms Laboratory
1313 Halley Circle, Norman, Oklahoma 73069

for

Grant No. F49620-95-1-0320

**Doppler Radar Wind Analysis for
Climate Model Verification and Numerical Weather Prediction**

1. Objectives:

The research objectives remain basically the same as originally proposed (in section I of original proposal). In addition to the goals described in section III of the proposal (revised in our letter of 12 January, 1995), research effort was also made on developing a new variational method for computing the surface fluxes of sensible and latent heat.

2. Status of Effort:

Towards the research goals described in section IIIa-b of the revised proposal, effort has been made on combining the VAD technique with the simple adjoint method and least square method. The simple adjoint method and least square method can retrieve winds on a high resolution grid, but the area-averaged divergence of the retrieved wind field is found to be dependent on the grid resolution (see Fig. 1 and attached discussion). On the other hand, the VAD-estimated divergence can be quite accurate as shown by our recent study (Lu, Doviak and Crisp 1996, listed in 96 report). This suggests that the divergence profiles, estimated from application of Gauss's theorem at different radii, might be used as additional constraints to improve the simple adjoint and least square retrievals.

Towards the research goal described in section IIIc of the original proposal, we have been working on combining background information from O-LAPS (the Oklahoma Local Analysis and Prediction System) into the simple adjoint method and least square method to improve the wind retrievals. The retrieved winds can then be used together with surface mesonet data to improve the O-LAPS analysis and short-term weather prediction. Some preliminary results are reported in section 3a.

3. Accomplishments:

a. Using single-Doppler retrievals to improve short-term prediction

The least square method has been upgraded by including background wind fields from O-LAPS (the Oklahoma Local Analysis and Prediction System). The upgraded method is applied to single-Doppler data collected by the NEXRAD radar at Twin Lakes on 7 May during the 1995 Oklahoma Vortex Field Experiment. The retrieved winds are used together with surface mesonet data to improve the initial condition for the ARPS model's short-term prediction. The preliminary results are encouraging (see Figs. 2-4 and attached discussion).

b. Computation of surface fluxes

To overcome the drawbacks of conventionally used Bowen Ratio Energy Balance Technique (BREB) and Profile method (PROF), a variational method has been developed to compute the surface fluxes of sensible and latent heat by using data from the surface energy and radiation balance systems (SERBS). This method makes a better and more complete use of the data and the constraints provided by the surface energy balance equation and the similarity profile equations (publications #1).

c. Generalized adjoint for physical processes

The classic adjoint theory derived for differentiable systems of equations is not applicable to systems with parameterized discontinuities. The classic theory was recently generalized (see 96 report), and the generalized adjoint formulations are further developed to deal with various complex situations in numerical models (publications #2-3).

4. Personnel Supported:

In FY 96-97, this grant supported the PI, Dr. Qin Xu, (12.5% FTE for 3 months in 1996), three graduate students (two in meteorology for thesis-related research and one in computer science for code development) and one research scientist.

5. Publications:

1. Xu, Q., and C. Qiu, 1997: A Variational method for computing surface heat fluxes from ARM Surface Energy and Radiation Balance Systems. ***J. Appl. Meteor.***, **36**, 3-11.
2. Xu, Q., 1997: Generalized adjoint for physical processes with parameterized discontinuities – Part III: Multiple threshold conditions. ***J. Atmos. Sci.*** (accepted).
3. Xu, Q., 1997: Generalized adjoint for physical processes with parameterized discontinuities – Part IV: Problems in time discretization. ***J. Atmos. Sci.*** (accepted).

6. Interactions/Transitions

The variational technique for computing surface fluxes (Xu and Qiu, 1997) may be useful as and objective method for the third generation of the NCAR Portable Automated Mesonet (PAM) surface meteorological station. The computational code was given to Dr. Horst at the NCAR Surface Sensing Group, and he utilized the code in the development of their model.

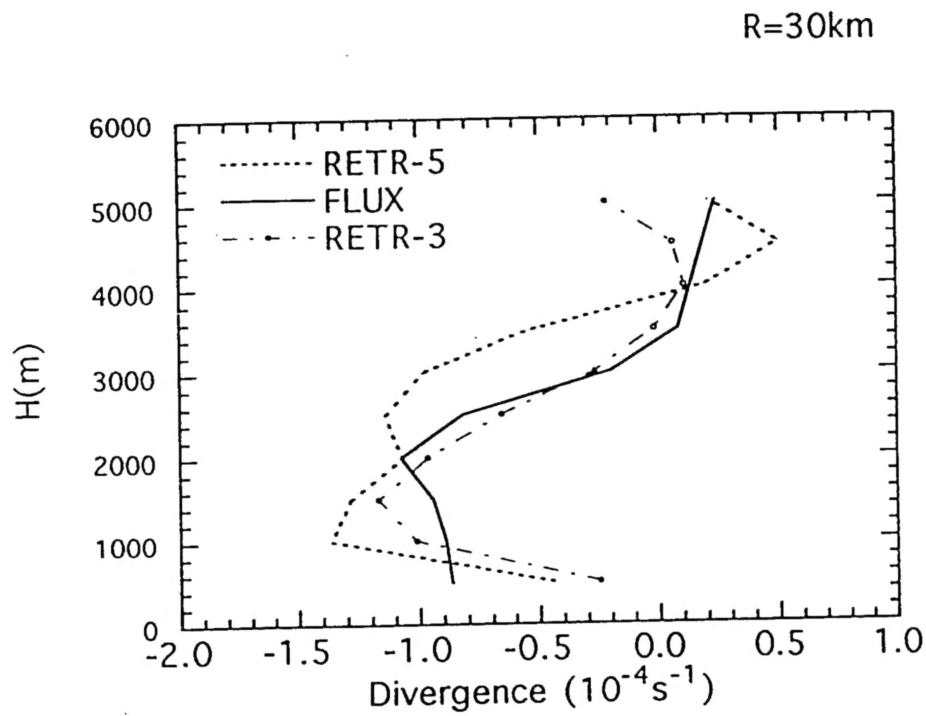

Fig. 1. Vertical profiles of wind divergence averaged over the area within 30 km radius from the NEXRAD radar at Twin Lakes, Oklahoma, at 18:02, 7 May, 1995. The solid profile is estimated from the observed radial winds (fluxes) integrated along the circular boundary of the area. The remaining two profiles are obtained from the retrieved wind fields (by the least square method) with different grid resolutions: 5 km for the dotted profile, and 3 km for the dash-dotted profile.

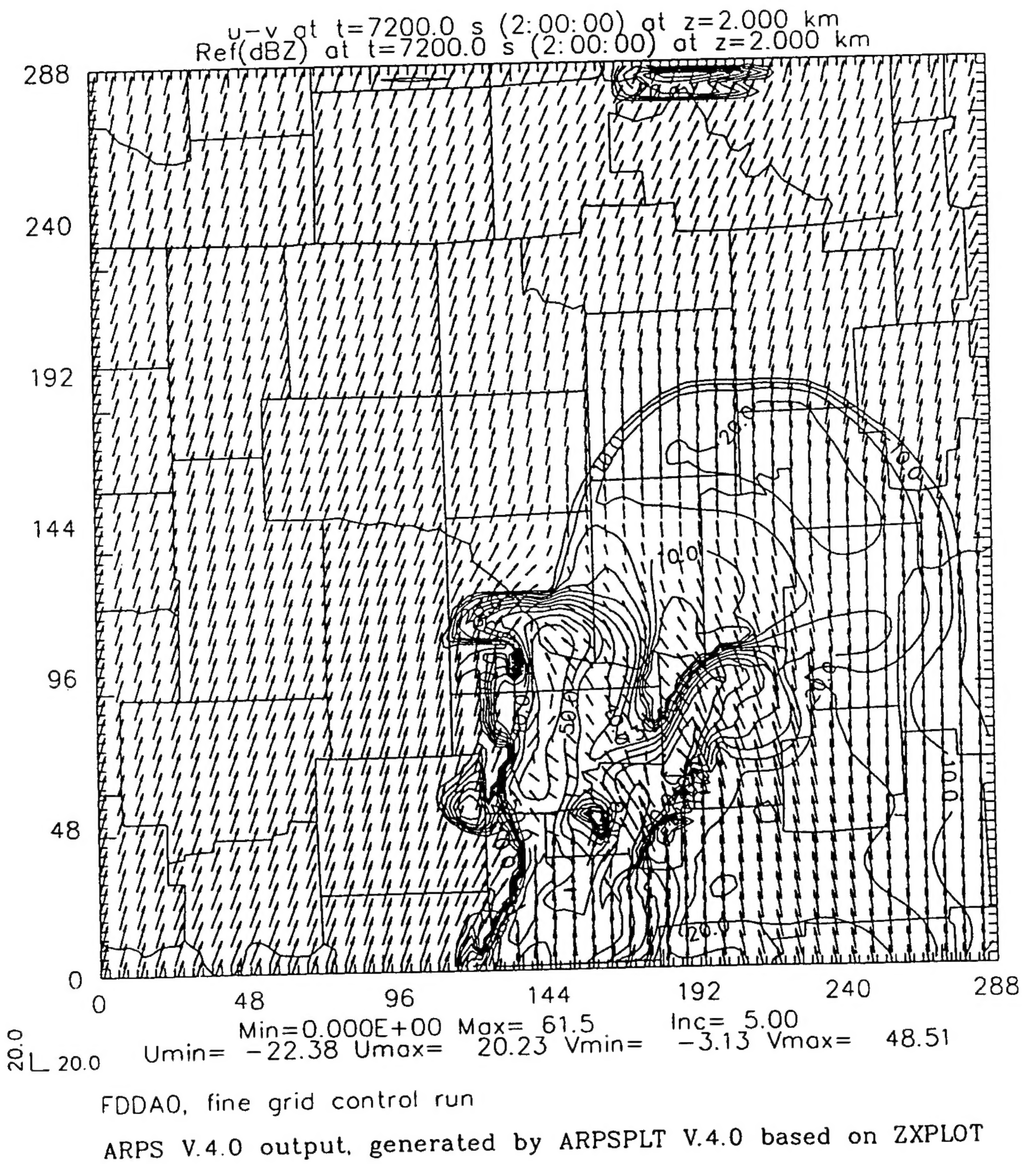

Fig. 2. Horizontal winds and reflectivity contours (valid at 20:02, 7 May, 1995) predicted by the ARPS model in two hours without using the retrieved winds and mesonet data in the initial analysis (at 18:02).

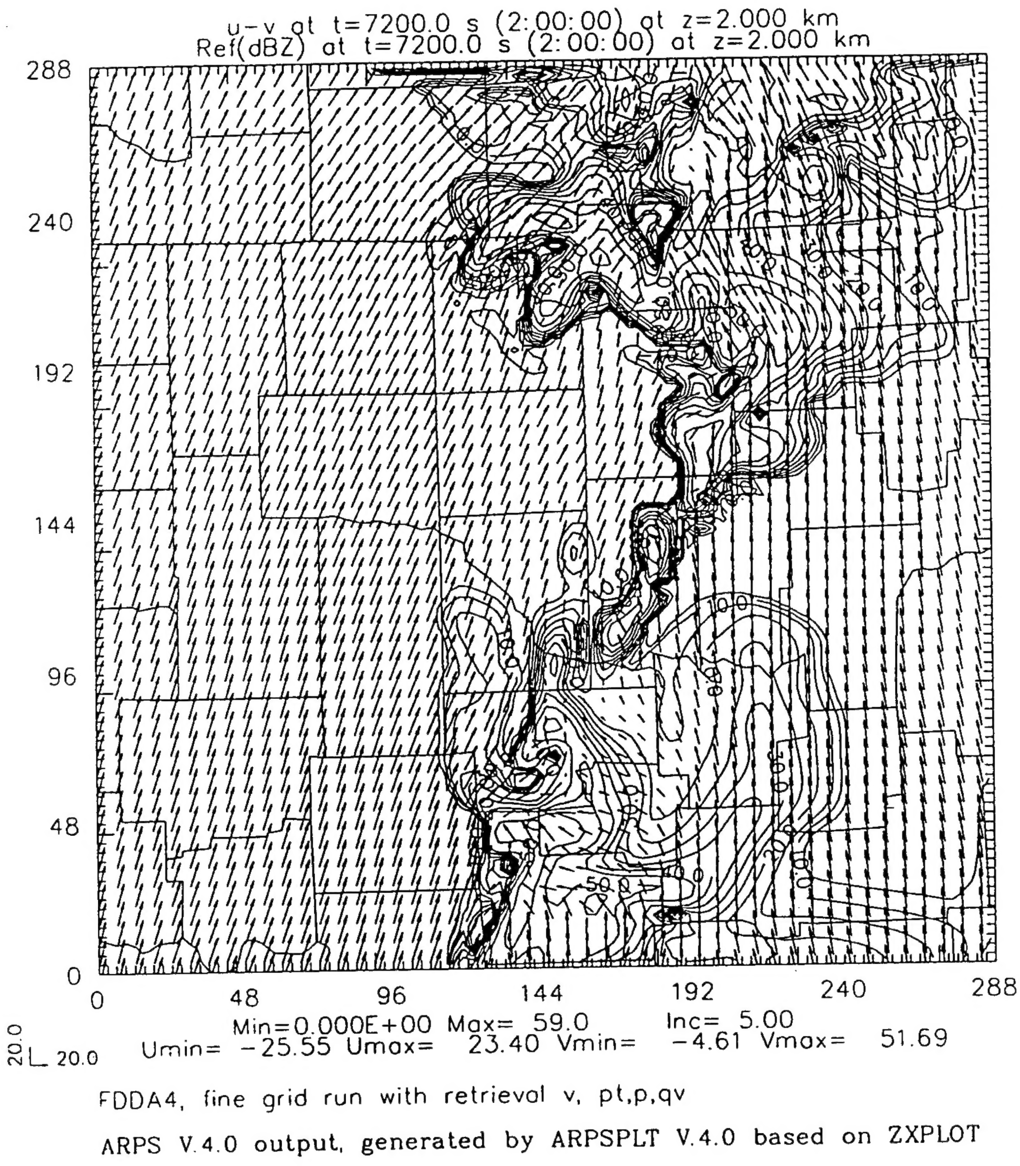

Fig. 3. As in Fig. 2, but with the retrieved winds and mesonet data used in the analysis at the initial time.

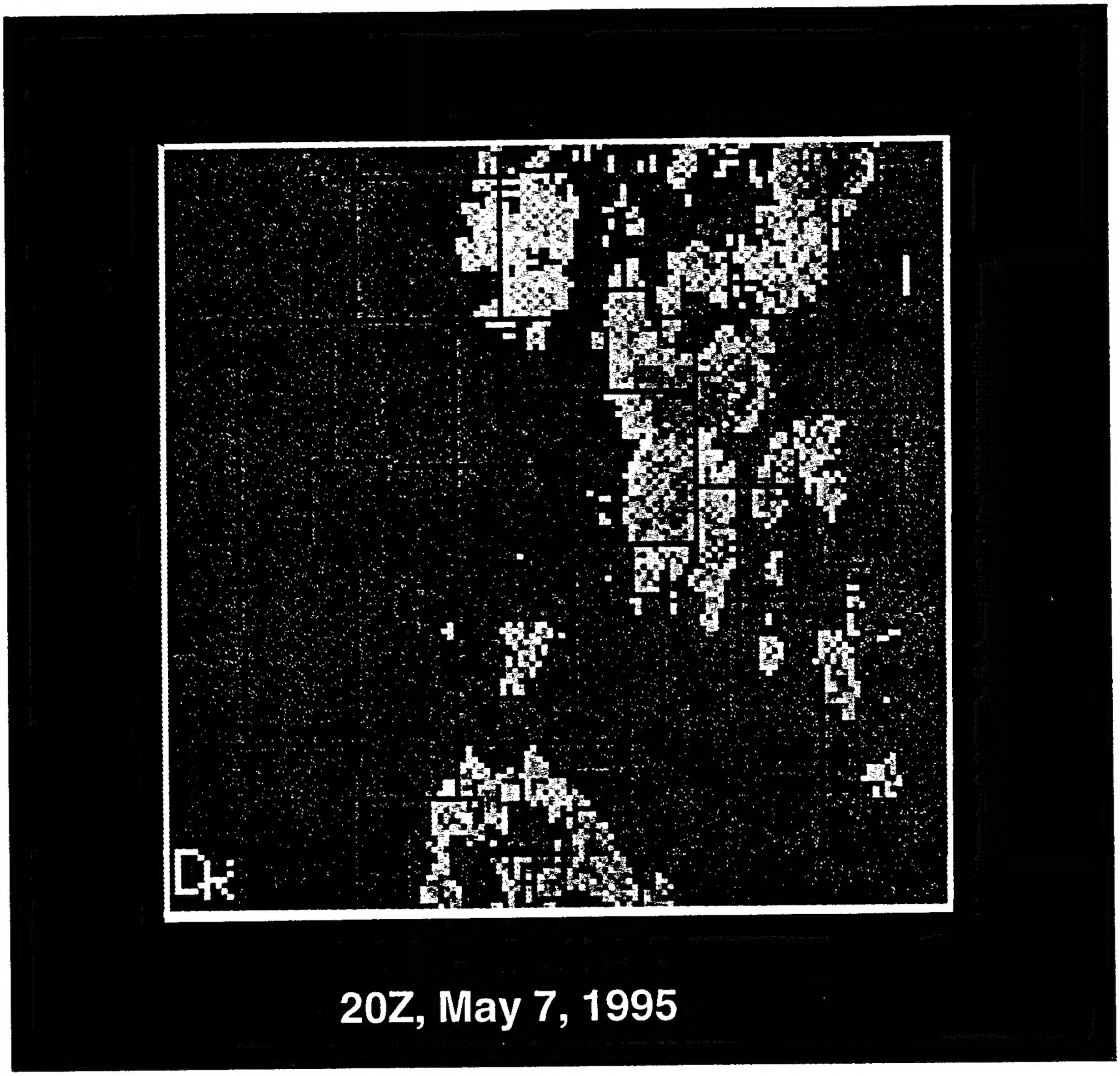

Fig.4. Radar reflectivity observed by the NEXRAD radar at Twin Lakes at 20 Z, May 7, 1995 during the Vortex-95 field experiment.

Discussion of Figures 1-4

Figure 1:

In Fig. 1, the solid profile is computed, based on Gauss's theorem, from line-integration of the observed radial winds along the circular boundary of the area. Since the radial winds are nearly horizontal at 30 km radius, this line integration should give a quite accurate estimate of the horizontal divergence averaged over the area of 30 km radius, similar to the VAD-estimated divergence (Lu, Doviak and Crisp 1996, listed in 96 report). The remaining two profiles are obtained from horizontal-area-integration of the divergence fields computed from two retrieved wind fields by using the same least square method but different grid resolutions: 5 km for the dotted profile, and 3 km for the dash-dotted profile. The difference between these two profiles indicate that the area-averaged divergence of the retrieved wind field is dependent on the grid resolution, although the two retrieved wind fields are similar in their general flow patterns (not shown). The errors of these two profiles can be estimated by their differences from the solid profile. The solid profile should be as accurate as VAD-estimated divergence (about 1x10 raised to the -6 power), and thus might be used as additional constraints to improve the simple adjoint and least square retrievals.

Figure 2-4:

Presented herein are prediction results from the VORTEX squall line case of 7 May 1995. The purpose is to test the impact of the retrieved wind (by using the updated least square method) and thermodynamic fields from the NEXRAD data (collected by the KTLX WSR-88D radar at Twin Lakes, Oklahoma) on the initial analysis and subsequent prediction (made by the ARPS model).

Two experiments are described here: (i) a control run with no radar and mesonet data, and (ii) a test run utilizing the retrieved wind and thermodynamic fields from radar and mesonet data. In both cases, the ARPS computational domain consisted of a fine grid (3 km) covering 300x300 km^2 nested within a coarse grid (9 km). RUC forecast fields were used as boundary conditions for both runs. For the test run, five consecutive scans of KTLX data (at 6 minutes intervals) were used to retrieve the wind fields at three consecutive time levels. These retrieved wind data were then used to retrieved the thermodynamic fields with the O-LAPS, which is now called ADAS (ARPS Data Analysis System).

The impact of the radar data is particularly notable two hours into the forecast. Figs. 2-3 depict the reflectivity contours (computed from a semi-empirical rainwater-reflectivity relation) and velocity vectors at z=2 km. The main differences between the control run (Fig. 2) and the test run (Fig. 3) appear in northern Oklahoma. Comparing the predicted reflectivities with the observations (Fig. 4), we can see that the area coverage and intensity of the precipitation in northern Oklahoma is reasonably well predicted in the test run but not in the control run.

Summary of Research Effort in FY 96-97

Qin Xu (PI) and Richard J. Doviak (PI)

Project Title: Doppler Radar Wind Analysis for
Climate Model Verification and Numerical Weather Prediction

Grant No. F49620-95-1-0320

1. Single-Doppler retrievals and their use in improving short-term prediction

Effort has been made on combining the VAD technique with the simple adjoint method and least square method. The simple adjoint method and least square method can retrieve winds on a high resolution grid, but the area-averaged divergence of the retrieved wind field is found to be dependent on the grid resolution (Fig. 1 and attached discussion). On the other hand, the VAD-estimated divergence can be quite accurate as shown by our recent study (Lu, Doviak and Crisp 1996, listed in 96 report). This suggests that the divergence profiles, estimated from application of Gauss's theorem at different radii, might be used as additional constraints to improve the simple adjoint and least square retrievals.

The least square method has been upgraded by including background wind fields from O-LAPS (the Oklahoma Local Analysis and Prediction System). The upgraded method is applied to single-Doppler data collected by the NEXRAD radar at Twin Lakes on 7 May during the 1995 Oklahoma Vortex Field Experiment. The retrieved winds are used together with surface mesonet data to improve the initial condition for the ARPS model's short-term prediction. The preliminary results are encouraging (see Figs. 2-4 and attached discussion).

2. Computation of surface fluxes

To overcome the drawbacks of conventionally used Bowen Ratio Energy Balance Technique (BREB) and Profile method (PROF), a variational method has been developed to compute the surface fluxes of sensible and latent heat by using data from the surface energy and radiation balance systems (SERBS). This method makes a better and more complete use of the data and the constraints provided by the surface energy balance equation and the similarity profile equations (publications #1). The method may be useful as and objective method for the third generation of the NCAR Portable Automated Mesonet (PAM) surface meteorological station, and the computational code was given to the NCAR Surface Sensing Group.

3. Generalized adjoint for physical processes

The classic adjoint theory derived for differentiable systems of equations is not applicable to systems with parameterized discontinuities. The classic theory was recently generalized (see 96 report), and the generalized adjoint formulations are further developed to deal with various complex situations in numerical models (publications #2-3).